

# Magnetic Monopole Search with the SLIM experiment

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## Abstract

The SLIM experiment was an array of 427 m<sup>2</sup> of nuclear track detectors, exposed at a high altitude laboratory (Chacaltaya, Bolivia, 5230 m a.s.l.), for ~4.22 years. SLIM was sensitive to downgoing intermediate mass magnetic monopoles with masses of 10<sup>5</sup> GeV ≤ M<sub>M</sub> ≤ 10<sup>12</sup> GeV. The analysis of the full detector gives a flux upper limit of 1.3 × 10<sup>-15</sup> cm<sup>-2</sup>s<sup>-1</sup>sr<sup>-1</sup> (90% C.L.) for downgoing fast intermediate mass magnetic monopoles.

**Key words:** magnetic monopoles, rare particles, nuclear track detector

## 1. Introduction

P.A.M. Dirac introduced the concept of the magnetic charge "g" in order to explain the quantization of the electric charge "e". He obtained the formula  $eg = n\hbar c/2$ , from which  $g = ng_D = n\hbar c/2e = n68.5e$ , where  $n = 1, 2, 3, \dots$  (Dirac, 1931). Magnetic Monopoles (MMs) possessing an electric charge and bound systems of a MM with an atomic nucleus are called dyons (Giacomelli, 2000).

The electric charge is naturally quantified in Grand Unified Theories (GUT) of the strong and electroweak interactions which describes phase transitions of the early Universe at the mass scale  $M_G \sim 10^{14} \div 10^{15}$  GeV. These models imply the existence of *GUT monopoles* with calculable properties such as their masses. The MM mass is related to the mass of the X, Y carriers of the unified interaction,  $m_M \geq m_X/G$ , where G is the dimensionless unified coupling constant at energies  $E \approx m_X$ . If  $m_X \approx 10^{14} - 10^{15}$  GeV and  $G \approx 0.025$ ,  $m_M > 10^{16} - 10^{17}$  GeV (Ambrosio, 2002).

Some GUT models and Supersymmetric models predict *Intermediate Mass Monopoles* (IMMs) with masses  $m_M \sim 10^5 \div 10^{12}$  GeV and magnetic charges of integer multiples of  $g_D$ . IMMs may have been produced in later phase transitions in the early Universe and could be present in the cosmic radiation and may be accelerated up to relativistic velocities in one coherent galactic magnetic field domain. Thus one may look for downgoing, fast ( $\beta \geq 0.03$ ) heavily ionizing IMMs (Balestra, 2008; Giacomelli, 2007).

The exposure at a high altitude laboratory allows to search for IMMs of lower masses, higher charges and lower velocities. The main purpose of the SLIM (Search for LIght magnetic

Monopoles) experiment deployed at the Chacaltaya laboratory in Bolivia at 5230 m a.s.l., was the search for IMMs (Balestra, 2008; Bakari, 2000). Fig. 1 shows the accessible regions in the plane (mass,  $\beta$ ) for experiments located at different altitudes. The SLIM detector was also sensitive to strange quark matter nuggets (Witten, 1984) and Q-balls (Coleman, 1985); the results on these dark matter candidates are discussed in (Shanoun, 2008).

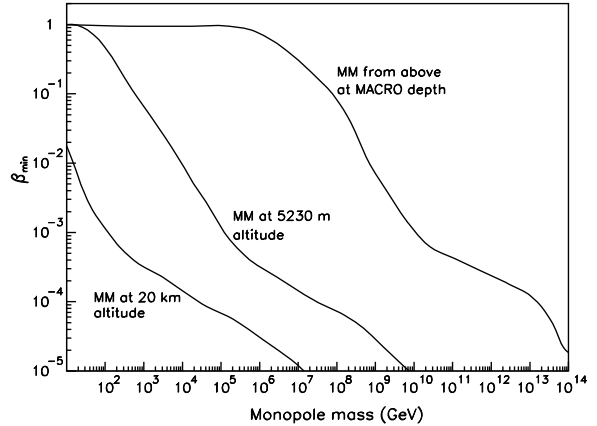


Figure 1: Accessible regions in the plane (mass,  $\beta$ ) for monopoles with magnetic charge  $g = g_D$  coming from above for experiments at altitudes of 20 km, at 5230 m a.s.l., and for an underground detector.

## 2. Experimental procedure

The SLIM detection area (427 m<sup>2</sup>) was an array organized into 7410 modules, each one of area 24 × 24 cm<sup>2</sup> (Bakari, 2000). All modules were made up of: three layers of CR39<sup>®</sup> <sup>1</sup>,

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<sup>1</sup>The SLIM CR39 was produced by the Intercast Europe Co, Parma, Italy according to our specifications.

each 1.4 mm thick; 3 layers of Makrofol DE<sup>®</sup> 2, each 0.48 mm thick; 2 layers of Lexan each 0.25 mm thick and one layer of aluminum absorber 1 mm thick (see Fig. 2). An special batch of 50 m<sup>2</sup> of the total area, was composed of stacks using CR39 containing 0.1% of DOP additive. Each stack was sealed in an aluminized plastic bag (125  $\mu$ m thick) filled with dry air at a pressure of 1 bar. The stacks were deployed under the roof of the Chacaltaya Laboratory, roughly 4 m above ground. The

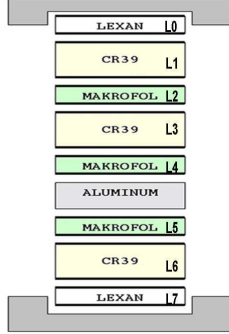


Figure 2: SLIM module composition.

geomagnetic cut-off for cosmic rays at the detector latitude is  $\sim 12.5$  GV. Environmental conditions at the Chacaltaya lab are: atmospheric pressure  $\sim 0.5$  atm; mean temperature  $12^\circ\text{C}$ , oscillating from  $0$  to  $30^\circ\text{C}$ ; the radon concentration is  $\sim 40\text{--}50$  Bq/m<sup>3</sup>. The neutron flux measured with BTI bubble counters at the detector site, in the range from few hundred keV to  $\sim 20$  MeV is  $(1.7 \pm 0.8) \times 10^{-2} \text{ cm}^{-2} \text{ s}^{-1}$  (Zanini, 2001).

**Etching procedures and NTD calibrations:** The passage of a magnetic monopole in NTDs, such as CR39, causes structural line damage in the polymer (forming the so called “latent track”). Since IMMs have a constant energy loss through the stacks, the subsequent chemical etching should result in collinear etch-pit cones of equal size on both faces of each detector sheet. In order to increase the detector “signal to noise” ratio different etching conditions (Cecchini, 2001; Balestra, 2007; Togo 2008) were defined. The so-called “strong etching” technique produce better surface quality and larger post-etched cones. This makes etch pits easier to detect under visual scanning. Strong etching was used to analyze the top-most CR39 sheet in each module. “Soft etching” was applied to the other CR39 layers in a module if a candidate track was found after the first scan.

For CR39 and CR39(DOP) the strong etching conditions were: 8N KOH + 1.5% ethyl alcohol at  $75^\circ\text{C}$  for 30 hours. The bulk etching velocities were  $v_B = 7.2 \pm 0.4 \mu\text{m/h}$  and  $v_B = 5.9 \pm 0.3 \mu\text{m/h}$  for CR39 and CR39(DOP), respectively. The soft etching conditions were 6N NaOH + 1% ethyl alcohol at  $70^\circ\text{C}$  for 40 hours for CR39 and CR39(DOP). The bulk etching rates were  $v_B = 1.25 \pm 0.02 \mu\text{m/h}$  and  $v_B = 0.98 \pm 0.02 \mu\text{m/h}$  for CR39 and CR39(DOP), respectively. Makrofol NTDs were etched in 6N KOH + 20% ethyl alcohol at  $50^\circ\text{C}$  for 10 hours; the bulk etch velocity was  $v_B = 3.4 \mu\text{m/h}$ .

**NTD Calibrations:** The CR39 and Makrofol nuclear track de-

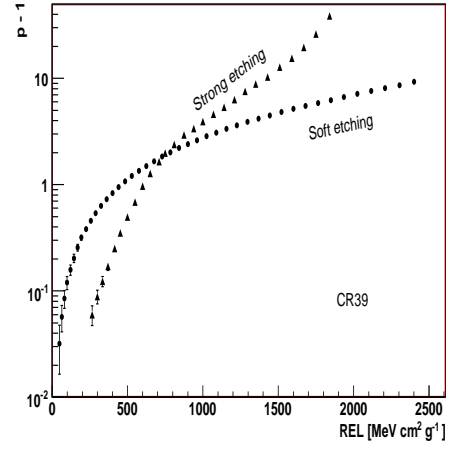


Figure 3: Reduced etch rate ( $p-1$ ) vs. REL in CR39 for strong and soft etching.

tectors were calibrated with 158 A GeV In<sup>49+</sup> and Pb<sup>82+</sup> beams at the CERN SPS and 1 A GeV Fe<sup>26+</sup> at the AGS synchrotron of the Brookhaven National Laboratory (BNL). The calibration layout was a standard one with a fragmentation target and CR39 (plus Makrofol) NTDs in front and behind the target (Cecchini, 2008). The detector sheets behind the target detected both primary ions and nuclear fragments.

We recall that the formation of etch-pit cones (“tracks”) in NTDs is regulated by the bulk etching rate,  $v_B$ , and the track etching rate,  $v_T$ , *i.e.* the velocities at which the undamaged and damaged materials (along the particle trajectory), are etched out. Etch-pit cones are formed if  $v_T > v_B$ . The response of the CR39 detector is measured by the etching rate ratio  $p = v_T/v_B$ . In the calibration procedure, the track’s area of each fragment

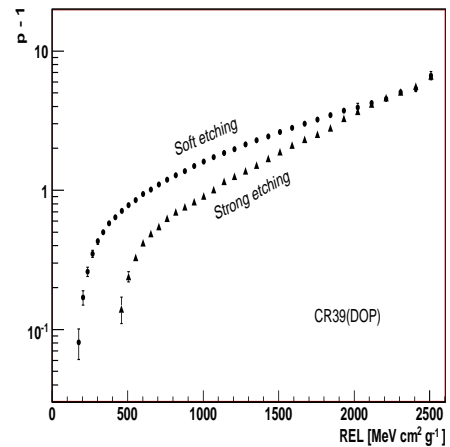


Figure 4: Reduced etch rate ( $p-1$ ) vs. REL for strong and soft etching, for CR39(DOP).

and survival beam ions are measured, and the  $Z$  of each resolved peak is identified via the average measured base areas.

For each calibration peak the  $Z/\beta$  is obtained and the reduced etch rate ( $p-1$ ) is computed. The Restricted Energy Loss (REL) due to ionization and nuclear scattering is evaluated, thus ar-

<sup>2</sup>Manufactured by Bayer AG, Leverkusen, Germany.

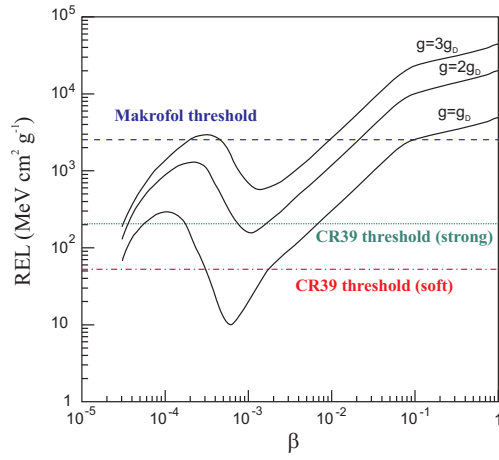


Figure 5: REL vs beta for magnetic monopoles with  $g = g_D, 2g_D, 3g_D$ . The dashed lines represent the CR39 thresholds in soft and strong etching conditions and the Makrofol threshold.

iving to the calibration curve  $(p - 1)$  vs. REL. Fig. 3 and 4 shows the cases for both strong and soft etching conditions of the CR39 and CR39 with DOP, respectively. The detection thresholds are listed in table 1.

	detector type	$Z/\beta$	REL [MeVcm <sup>2</sup> /g]
strong	CR39	14	200
	CR39 DOP	21	460
	Makrofol	50	2500
soft	CR39	7	50
	CR39 DOP	13	170

Table 1: Detection thresholds  $z/\beta$  and restricted energy loss REL [MeVcm<sup>2</sup>/g] for CR39, CR39 DOP, and Makrofol, respectively.

For magnetic monopoles with  $g = g_D, 2g_D, 3g_D$  we computed the REL as a function of  $\beta$  taking into account electronic and nuclear energy losses, see Fig. 5 (Derkaoui, 1999).

With the used etching conditions, the CR39 allows the detection of (i) MMs with  $g = g_D$  for  $\beta \sim 10^{-4}$  and for  $\beta > 10^{-2}$ ; (ii) MMs with  $g = 2g_D$  for  $\beta$  around  $10^{-4}$  and for  $\beta > 4 \times 10^{-3}$ ; (iii) the whole  $\beta$ -range of  $4 \cdot 10^{-5} < \beta < 1$  is accessible for MMs with  $g > 2g_D$  and for dyons.

For the Makrofol polycarbonate the detection threshold is at  $Z/\beta \sim 50$  and  $REL \sim 2.5 \text{ GeV cm}^2 \text{ g}^{-1}$  (Balestra, 2007); for this reason the use of Makrofol is restricted to the search for fast MMs.

**Neutron induced background:** A statistical study of the background tracks in the top-most CR39 layer, generated only by neutrons was made using Monte Carlo (MC) simulations. The neutron spectrum measured at the SLIM site is shown in Fig. 6, plotted as the intensity times the energy of the neutrons vs. their energy (Zanini, 2001), was used in the simulations. The CR39 polymer was defined by its chemical formula, its density and its post-etched (strong etching conditions) dimensions (Medinaceli, 2008).

For the exposure time, the total number of neutrons impinging on the detector was calculated, and the relative abundances

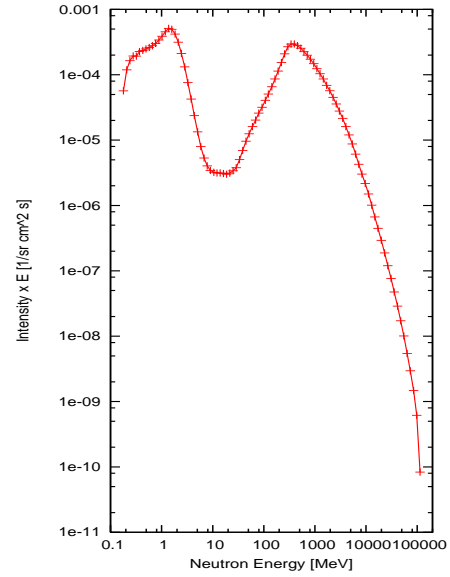


Figure 6: Wide range spectrometer: experimental neutron spectrum measured at Chacaltaya laboratory (5230 m a.s.l., 16°S 68°W), Zanini et al. (Zanini, 2001).

of secondary particles generated inside the CR39 was obtained. Fig. 7 shows the relative abundance of each kind of secondary particle, obtained as the ratio of the number of particles of one specie to the total number of secondaries. The most abundant particles produced are protons, with a relative abundance of the 52.4%, then <sup>12</sup>C isotopes (12.5%),  $\gamma$ -particles (9.5%), secondary neutrons (9.3%), <sup>16</sup>O isotopes (8.5%), and  $\alpha$  particles (~2%). The other species quoted on the plot contribute for less than ~1%. The most important mechanism for neutron interaction is elastic scattering with the constituent elements of CR39 (H, C, O). Inelastic scattering is the second most frequent process that neutrons undergo; by-products of this mechanism are  $\gamma$  and  $\alpha$  particles. A fraction of the 89% of the secondary

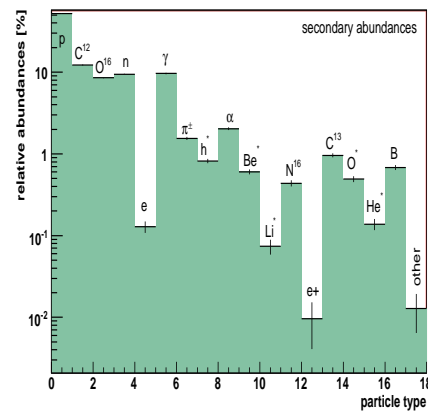


Figure 7: Secondary production inside CR39 (1000  $\mu\text{m}$ , post etched thick). The relative abundances (ratio of the number of secondaries of one specie and the total number of secondaries.) are expressed in percentage. Statistical errors are indicated with vertical bars.

protons have a REL distribution with values over the detector threshold (considering the  $REL_{th}$  obtained for strong etching).

All the  $^{12}\text{C}$ ,  $^{16}\text{O}$  ions and  $\alpha$ -particles have REL values over the  $REL_{th}$  value; this implies that all such particles are detectable by the SLIM detectors, neutrons mainly contribute to the surface background found on the top-most layer of CR39.

**Analysis:** The analysis of a SLIM module started by etching the uppermost CR39 sheet using strong conditions in order to reduce the CR39 thickness from 1.4 mm to  $\sim 0.9$  mm. After the strong etching, the CR39 sheet was scanned twice, with a stereo microscope, by different operators, with a  $3\times$  magnification optical lens, looking for any possible correspondence of etch pits on the two opposite surfaces. The measured single scan efficiency was about 99%; thus the double scan guarantees an efficiency of  $\sim 100\%$  for finding a possible signal.

Further observation of a “suspicious correspondence” was made with an optical  $20 \div 40\times$  stereo microscope and classified either as a defect or a candidate track. This latter was then examined by an optical microscope with  $6.3_{ob} \times 25_{oc}$  magnification and the axes of the base-cone ellipses in the front and back sides were measured. A track was defined as a “candidate” if the computed  $p$  and incident angle  $\theta$  on the front and back sides were equal to within 20%. For each candidate the azimuth angle  $\varphi$  and its position  $P$  referred to the fiducial marks were also determined. The uncertainties  $\Delta\theta$ ,  $\Delta\varphi$ ,  $\Delta z$  (the error associated to the depth of the lower-most layer of CR39) and  $\Delta P$  defined a “coincidence” area ( $< 0.5 \text{ cm}^2$ ) around the candidate expected position in the other layers, as shown in Fig. 8. In this case the lowermost CR39 layer was etched in soft etching conditions, and an accurate scan under an optical microscope with high magnification ( $500\times$  or  $1000\times$ ) was performed in a square region around the candidate expected position, which included the “coincidence” area. If a two-fold coincidence was detected, the CR39 middle layer was also analyzed.

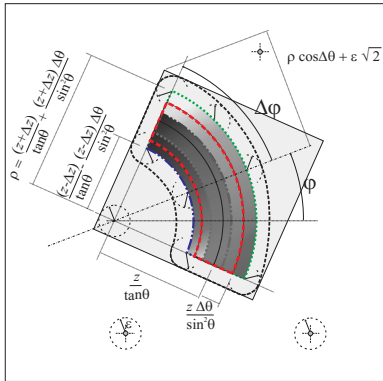


Figure 8: “Coincidence” area in which a possible candidate track located on the top layer will be searched for in the lower layer of the same module.

### 3. Results

Since no candidates were found, the 90% C.L. upper limit for a downgoing flux of IMM and for dyons was computed as

$$\phi = \frac{2.3}{(S\Omega) \cdot \Delta t \cdot \epsilon} \quad (1)$$

where  $\Delta t$  is the mean exposure time (4.22 y),  $S\Omega$  is the total acceptance,  $\epsilon$  is the scanning efficiency estimated to be  $\sim 1$ .

The global 90% C.L. upper limits for the flux of downgoing IMM and dyons with velocities  $\beta > 4 \cdot 10^{-5}$  were computed, the complete dependence with  $\beta$  is shown in Fig. 9. The flux limit for  $\beta > 0.03$  is  $\sim 1.3 \cdot 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ .

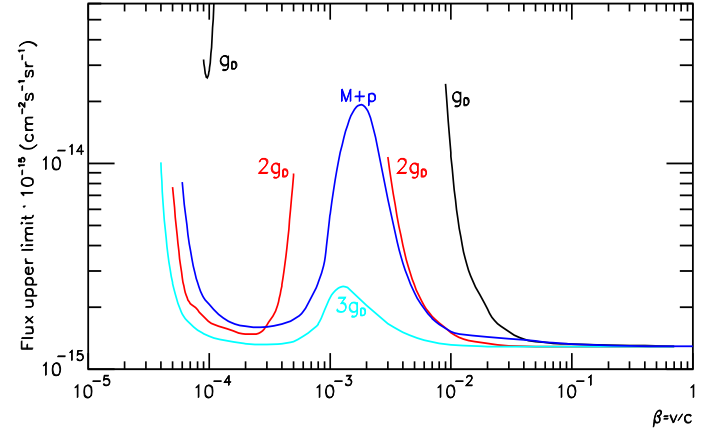


Figure 9: 90% C.L. upper limits for a downgoing flux of IMM with  $g = g_D$ ,  $2g_D$ ,  $3g_D$  and for dyons ( $M+p$ ,  $g = g_D$ ) plotted vs  $\beta$  (for strong etching). The poor limits at  $\beta \sim 10^{-3}$  arise because the REL is below the threshold (for  $g_D$  and  $2g_D$ ) or slightly above the threshold (for  $3g_D$  and dyons).

### Acknowledgements

We acknowledge the collaboration of E. Bottazzi, L. Degli Esposti and G. Grandi of INFN Bologna and the technical staff of the Chacaltaya Laboratory. We thank INFN and ICTP for providing grants for non-italian citizens.

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